Cosmic Comparisons

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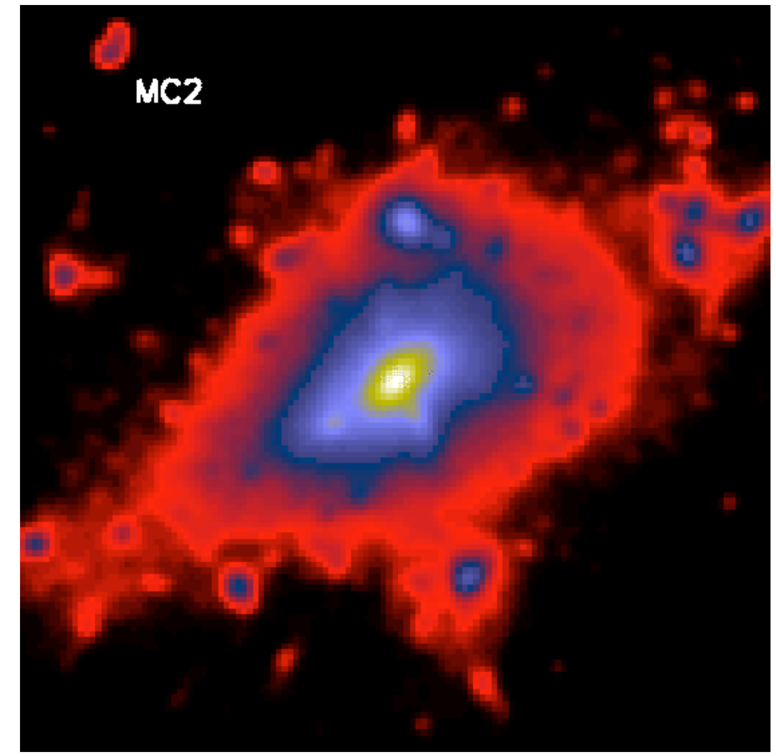
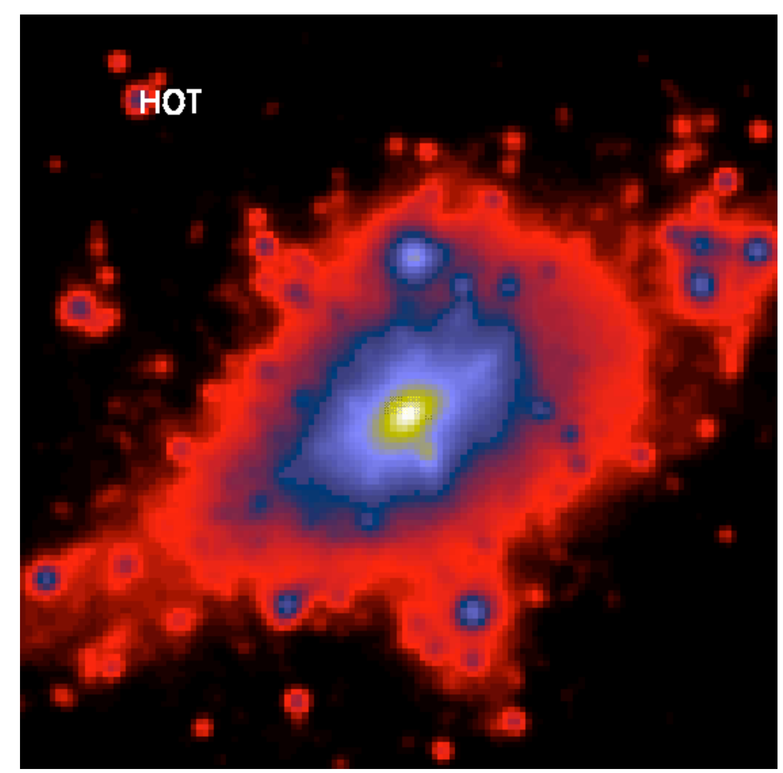
- Structure formation in the Universe is driven by the gravitational instability
- On large scales -- tens of Mpc -- linear theory provides a good description
- Nonlinear scales require a numerical approach
- Direct solution of Vlasov-Poisson equation is essentially impossible
- Hence need to use N-body methods
- How well do these methods work? Can they make useful predictions for next-generation surveys?





How do Cosmological Simulations Work?

- Assume evolution of large-scale Universe given by FRW equations ("concordance" parameters)
- Fix initial distribution at some high redshift using linear theory with reasonable assumption regarding primordial fluctuations (Harrison-Zeldovich), use Zeldovich approximation to get tracer particle initial conditions
- Evolve forward using N-body forces in an expanding Universe; add hydro if needed. Stringent requirements on S/T dynamic range.
- Add semianalytic methods to mock-up baryonic physics, feedback, etc.
- Make "observations" on simulation output; compare to reality

Precision Cosmology: Observations

SNAP (Supernova Acceleration Probe): 2000 supernovae on 15 square degree, 300-1000 square degree lensing survey,
Ωm, $\Omega \Lambda$, Ωtot: 1% accuracy,
ω: 4%, $d\omega/dt$: 10%

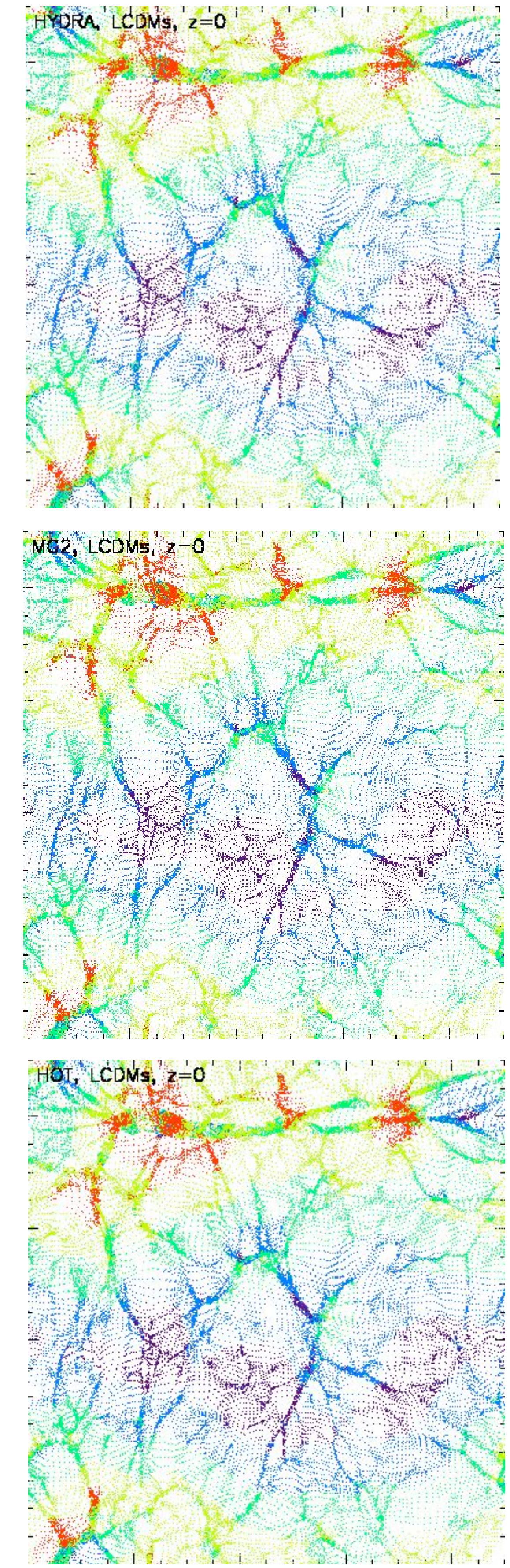
SPT (South Pole Telescope): 10 meter diameter telescope, many thousands of clusters, strong constraints on ω

LSST (Large Synoptic Survey Telescope): 8.4 meter, digital imaging across entire sky, supernovae etc., constraints on ω

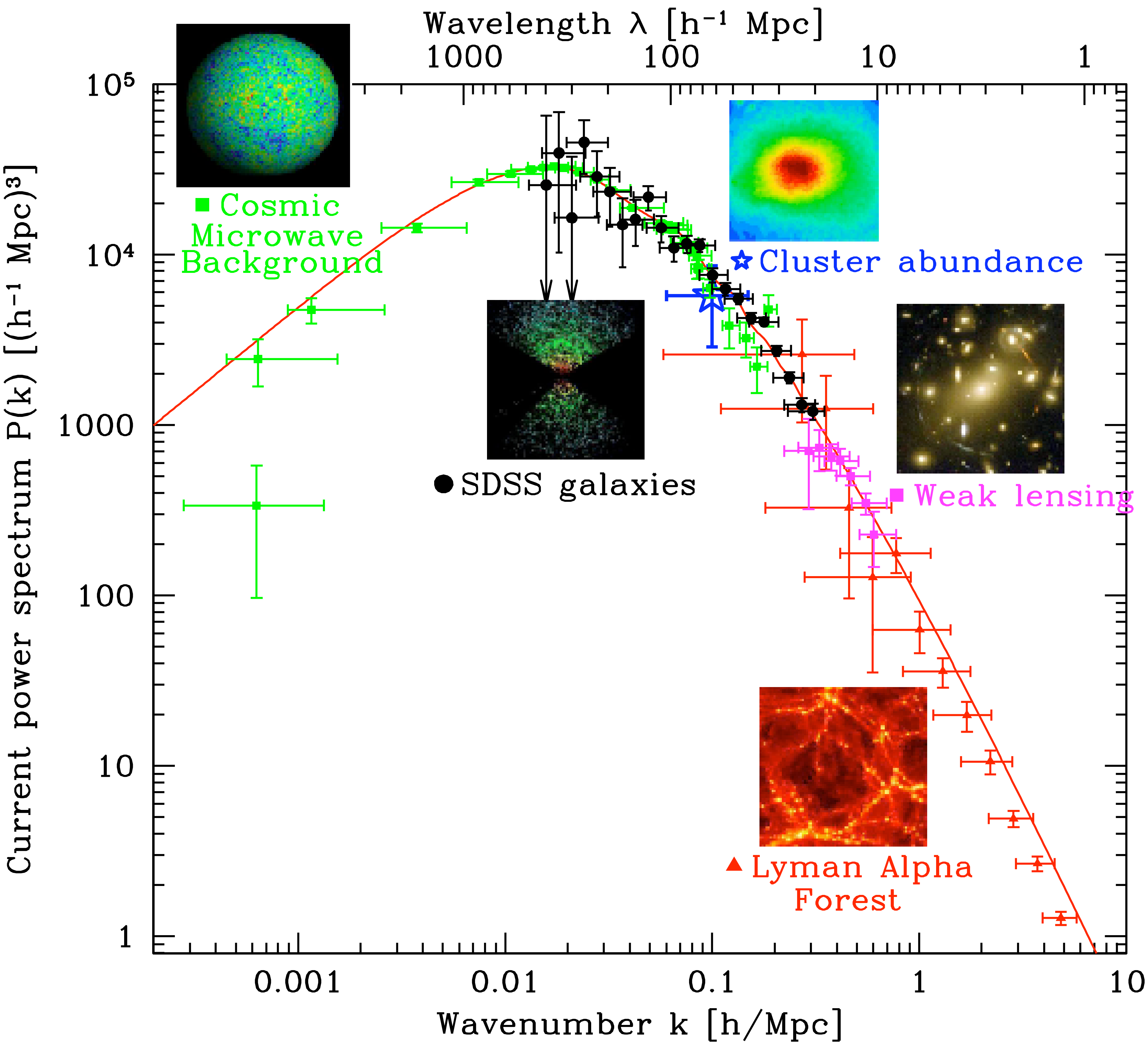
DES (Dark Energy Survey): galaxy cluster study, weak lensing, 2000 SNe Ia, constraints on ω at the one percent level

How Good are Simulations?

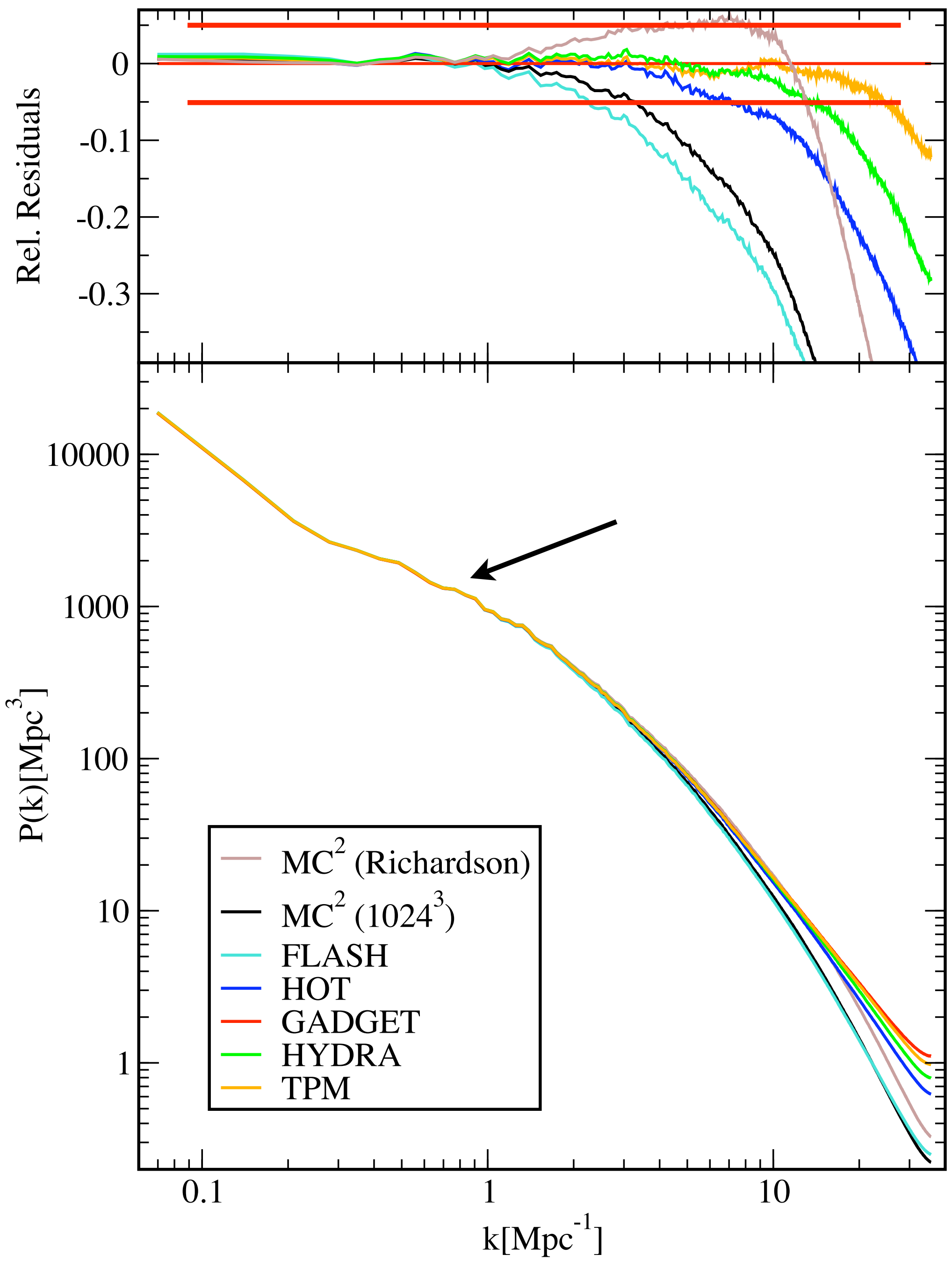
- Test/compare 6 N-body codes for LSS simulations
- 4 test problems: Zel'dovich pancake test, Santa Barbara cluster, 360 Mpc and 90 Mpc ΛCDM boxes
- Medium resolution regime: 10-100 kpc (baryons and hence gas dynamics, star formation etc. not yet important)
- Every code starts with identical initial conditions
- Results analyzed with the same set of analysis tools
- investigation of 2-point functions, velocity statistics, halo catalogs and statistics, etc.



The Mass Fluctuation Power Spectrum

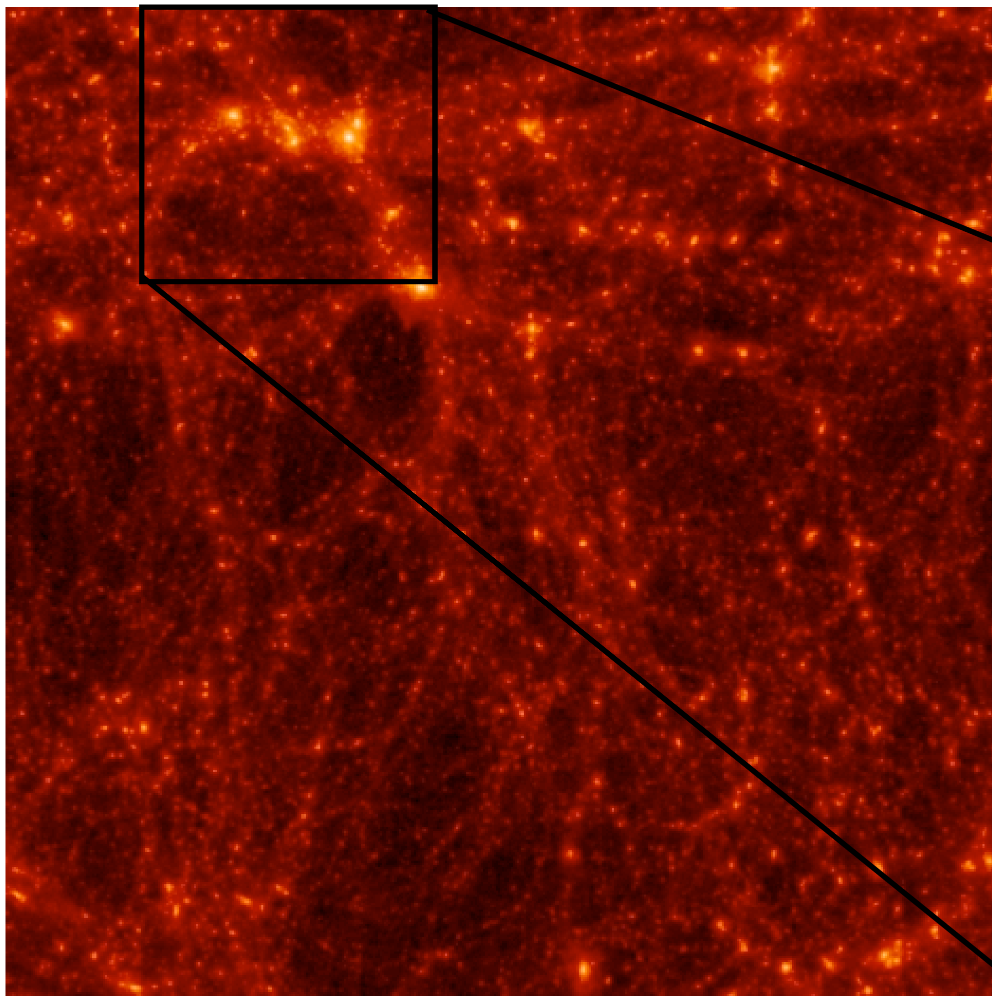


The Matter Power Spectrum

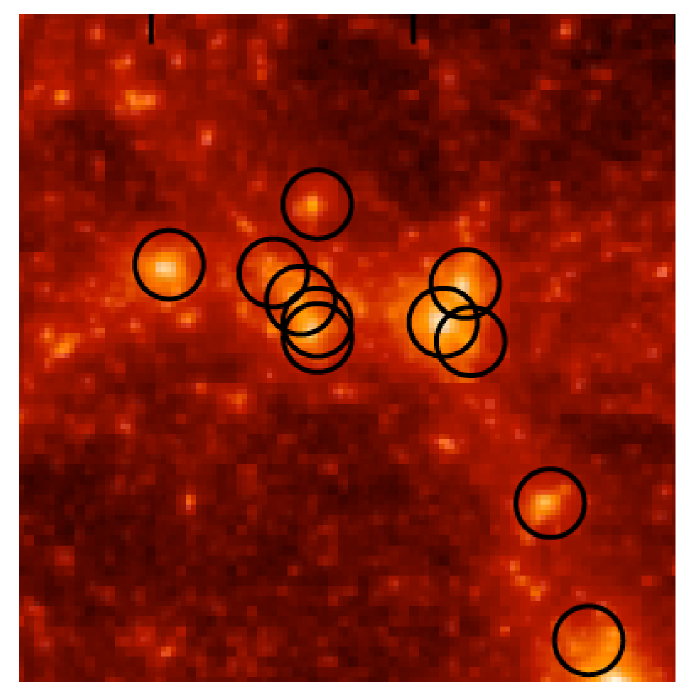


- P(k) measured from particles, 90 Mpc box, 256^3 particles
- Nonlinear turn-over at roughly k=0.7 / Mpc
- Two grid codes have less resolution, fall off earlier, but other codes have less than expected convergence
- FLASH: 40.8% fully refined
- Agreement: 5-10% over 2 decades
- Detailed analysis of code errors now underway
- Richardson extrapolation: use 512^3 and 1024^3 to predict "continuum"

Halo Statistics



- How to find/define them?
  → overdensity, nearest neighbor
- Observational relevance?
  → galaxy and cluster surveys



Marked halos ≥ 10,000 particles
Halos identified ≥ 10 particles
Particle mass ≈ $2 \cdot 10^9 M_\odot$

Halo Mass Function: Systematics

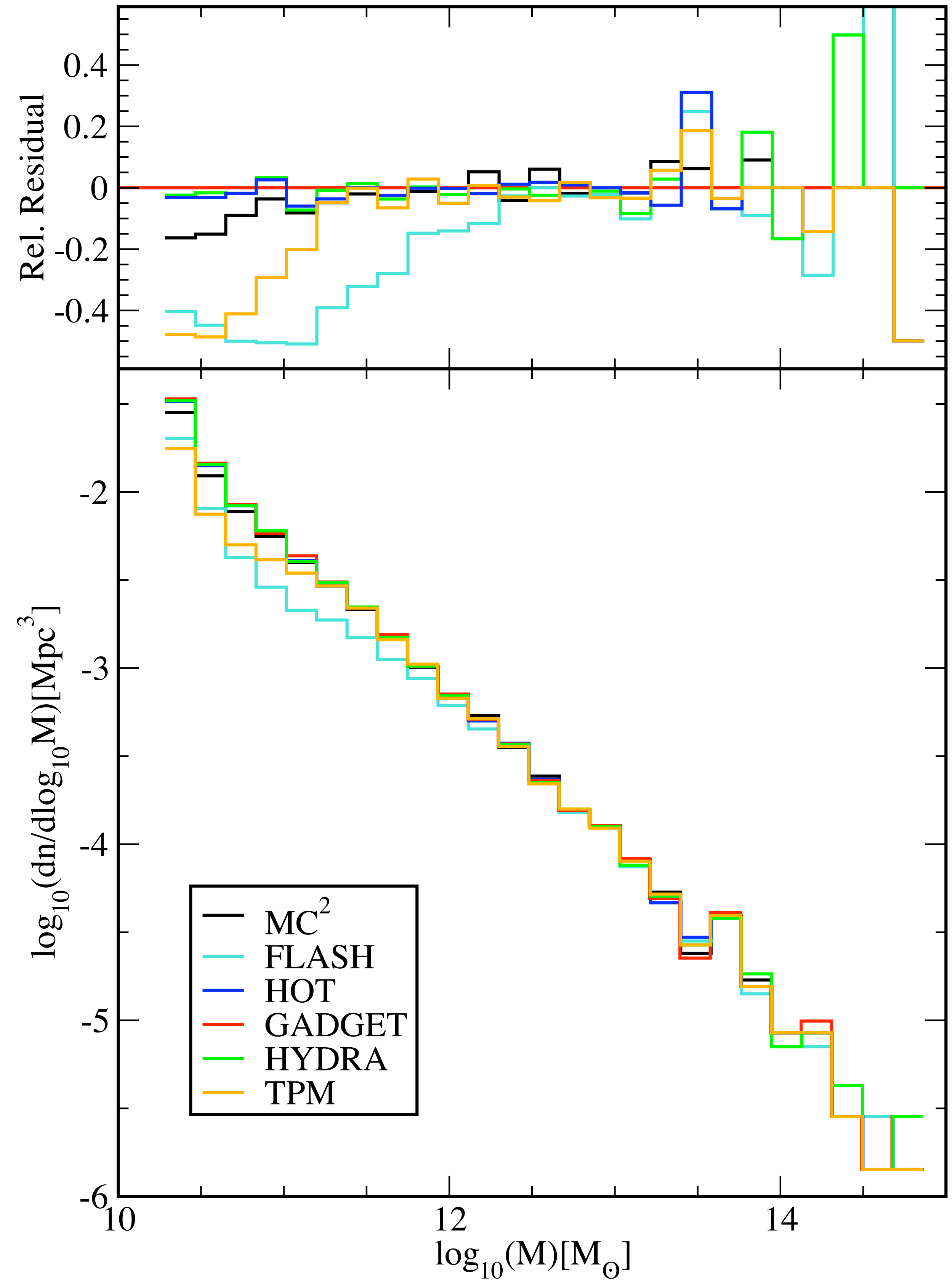
Comparing the halo mass function -- sensitive measure of dark energy at high mass end

Note low mass end sensitive to code resolution since small halos form first

But high-resolution codes can also have problems (e.g., TPM) if the short-range and long-range force hand-off is not correct

This is a particularly serious problem for AMR-type codes (how to set resolution thresholds?)

Note the several plus percent scatter also involves systematic effects from the halo finder



Concluding Remarks

- Comparison of six different codes (PM, AMR, Tree, TPM, AP^3M) in medium resolution regime
- Agreement at the general level of ~5%
- Larger disagreements usually understandable (e.g. insufficient force resolution)
- BUT: in order to achieve accuracy necessary for future surveys, this is NOT sufficient!
- WE NEED: development of multi-step error control methodology; perhaps hopeless for some tasks but maybe viable for others
- Cosmic Data ArXiv started -- reactions:
- D. Huterer (Chicago): "I saw and read your magnum opus, wow. Very, very nice. Such an analysis was badly needed and seems super-timely."
- V. Springel (MPA Garching): "This comparison is a heroic effort! (and a very useful one)"
- M. White, (Berkeley): "I saw your opus on the Web today. --- a pretty impressive piece of work, --- take me a while to work through it."
- R. Scoccimarro (NYU): "Thanks again for making this public, it is really very useful."

The Cosmic Data ArXiv

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Image: M81, Credit: N.A. Sharp (NOAO/AURA/NSF)